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RESEARCH PAPER

Poor Stem Form as a Potential Limitation to Private Investment in Koa Plantation Forestry in Hawaii

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Abstract Providing economic incentives to landholders is an effective way of promoting sustainable forest management, conservation and restoration. In Hawaii, the main native hardwood species with commercial value is *Acacia koa* (koa), but lack of successful examples of koa plantation forestry hinders private investment. Financial models, which have been offered to encourage investment, assume that a particular minimum volume of merchantable wood will be harvested at rotation age. No studies have been done to determine the appropriateness of the assumed volumes for koa plantations. Three 18- to 28-year-old koa plantations were studied to determine butt-log size, crown class and crop tree potential. Estimates of present and future merchantable sawtimber volume were made for each plantation. Results indicate that most existing plantation koa trees fork so close to the ground that they will produce little to no merchantable wood. Projected sawtimber yields from crop trees in these plantations at age 45 years are 10, 15 and 90 m^3/ha, which are below the 135 m^3/ha yield used in the most recent financial analysis of returns on investment in koa forestry. Relaxing the crop tree criteria gives higher volume yields, but two plantations still fall short of the assumed target yield by 43 and 52%.

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Given such shortfalls, returns on investment will be less than predicted by the financial analysis. Nevertheless, government offered financial incentives should compensate for lower volume yields and thus promote private investment in koa plantation forestry. Insect herbivory, genetic diversity, and low stand density contribute to poor stem form of plantation koa, and research is needed to quantify the relative importance of and interactions between these factors.

Keywords *Acacia koa* · Silviculture · Genetic tree improvement · Merchantable wood volume

Introduction

There is a growing consensus that effective conservation of native forest ecosystems and restoration of degraded forest and agricultural land cannot succeed if efforts are confined to legally protected, publicly owned forest reserves. Instead, a broader vision of conservation must applied across whole landscapes and eco-regions, and that necessarily involves complementary efforts by private landholders (Le Quesne and McNally 2005; Vanclay 2007). Motivating private investment in forestry is a dilemma for both developing and developed nations (Salafsky and Wollenberg 2000; Race and Stewart 2007; Maung and Yamamoto 2008). Providing economic incentives to landholders is increasingly viewed as the best way to motivate investment in sustainable native forest conservation and restoration (Pagiola et al. 2002; Pearce et al. 2003; Le Quesne and McNally 2005; Wunder 2005).

Salafsky and Wollenberg (2000) argued that in developing nations, livelihoods drive conservation, and if local stakeholders benefit directly from their conservation efforts, those efforts will have a high probability of success. In developed nations, governments offer various economic incentives to promote private forest investment (e.g. see Linden and Leppänen 2006). Non-government incentives are also being promoted in the form of carbon credits and other payments for environmental services made by outside interests to local landholders 'in return for adopting practices that secure ecosystem conservation and restoration' (Wunder 2005, p. 1).

The profitability of forestry ventures can depend not only on availability of government incentives to encourage plantation establishment, but also on having a merchantable product at rotation age together with an established market structure. The product in forestry ventures is often sawtimber, which requires trees with straight, single-stemmed, defect-free trunks. When grown in plantations some high-value temperate and tropical hardwood species, including *Eucalyptus camaldulensis*, *Juglans* spp. (walnut), *Swietenia macrophylla* (mahogany), *Acacia melanoxylon* (blackwood), *Cedrela odorata* and *Cordia alliodora*, tend to produce low-value, short butt logs and bolts due to crooked stems, low fork heights and delayed shedding of lower branches (Campbell and Dawson 1989; Otegbeye and Samarawira 1991; Cornelius 2001; Hummel 2001; Unwin et al. 2001; Erskine et al. 2005; Clark et al. 2008). For these and other broadleaved species with weak apical dominance, the wide spacing of plantations promotes trees with poor stem

form, large crowns and retention of lower branches (Evans 1992). Management interventions are usually needed to produce sawtimber-quality plantation trees.

Acacia koa and Conservation in Hawaii

Hawaii is a microcosm of global deforestation and forest degradation. Conversion of coastal and valley forests to agricultural and domestic uses began about 500 AD when the islands were first colonized by Polynesians. This accelerated greatly after 1798 with the arrival of Europeans and expanded to upland areas (Cuddihy and Stone 1990). Lowland forests were cleared for commercial crop production while the cooler, drier uplands were converted to pastures for livestock grazing (Tummons and Dawson 2002). The loss of biodiversity has been substantial, particularly for understory plant species on which some native forest birds depend (Scott et al. 1986).

Koa (*Acacia koa* A. Gray) is a fast-growing, nitrogen-fixing legume tree that is the second most common canopy dominant tree in Hawaiian forests (Hall 1904; Jenkins 1983). The history of koa forestry in Hawaii (1800–1970) has been one of exploitation. In the early 1800s, colonizing Europeans recognized that sizable tracts of koa forest across the island chain were located in areas suitable for agriculture. Extensive conversion of such land to non-forest uses began about the mid-1800s. In the early 1900s forests too wet for agriculture were incorporated into a forest reserve system meant to protect water supplies to lowland agricultural and urban areas (Hosmer 1959). Timber harvesting in the reserves was greatly restricted. To meet demand for koa wood, private landholders repeatedly opened their accessible forest land to loggers who became increasingly efficient at extracting useable wood, eventually harvesting even fallen logs that were partially buried in the soil. There was little interest in sustainable management of the koa resource, especially the development of silvicultural systems that would assure a long-term supply of koa wood. Despite the high economic, ecological and cultural values of the species, there are no documented examples of natural or planted stands of koa in Hawaii that have been through a full silvicultural rotation (i.e. establishment, stand improvement, harvest and re-establishment).

The continued degradation and loss of koa forests has negatively affected co-evolved native plants and animals (Baker et al. 2009). About 30% of the threatened and endangered plant species in Hawaii are associated with koa forests. Similarly, of Hawaii's 35 remaining native bird species, 30 species are found in koa forests and 17 of them are endangered. Conversion of high-elevation koa forests to cattle rangeland prevents the escape of native birds to cooler areas where avian malaria is absent. Reestablishment of koa forests to these upland areas is essential, especially if climate change raises the elevational zone in which malaria is readily transmitted (Benning et al. 2002). In addition to its value as wildlife habitat, koa has important cultural values, especially to native Hawaiians. Traditional racing canoes are carved out of koa logs, and koa furniture is a prized heirloom in many Hawaiian homes. The Hawaiian word '"koa'" connotes a warrior and relies on the image of a tall tree standing up in the forest. With the

disappearance of the koa forest many Native Hawaiians fear the loss of part of their traditional culture. While koa forestry is being promoted to Hawaii's landholders for its economic, cultural and conservation values (Goldstein et al. 2006; Pejchar and Press 2006), there is not similar local or scientific community support for the substitution of any non-native tree species for koa.

Since the 1970s, cattle ranching has become increasingly unprofitable in Hawaii. Ranchers have begun considering alternative land uses on large tracts of underused pasture. Many large ranches have subdivided and sold part of their land to generate income. At the same time, the large sugar cane plantations of the late 20th century have been subdivided and sold to individual landholders. Forest landholders in Hawaii typically own less than 10 ha, do not make their living from the land and value non-timber amenities such as wildlife habitat highly as well as hoping for eventual income from sustainable timber harvests (cf. Zhang et al. 2009). As of this writing, the forestry extension program of the University of Hawaii Cooperative Extension Service is working with 65 small (<20 ha) and 16 large (>200 ha) landholders who are actively involved in koa reforestation.

Koa forestry is being promoted as an alternative land use that might generate future income and restore the flow of ecosystem services that such forests provide. Forces of supply and demand have continued to raise prices for koa lumber (Table 1), and landholders have been presented with strong cases showing the potential profitability of koa forestry. The most recent financial analysis indicates that production koa forestry would be more profitable than cattle ranching, even without government incentives (Goldstein et al. 2006). With incentives, production koa forestry would be even more attractive. While some ranch lands still have a viable reserve of buried koa seeds from which a new forest can be regenerated, others do not. Koa forestry on the latter will be possible only in a plantation setting, at least initially. Unfortunately, the lack of management experience in both natural and plantation koa stands is deterring private landholders from engaging in koa forestry (Pejchar and Press 2006).

Table 1 Retail prices (US $/m^3) for the various grades of rough-finish koa lumber and raw logs, and the associated percentage price increases between 2005 and 2007

Lumber grade	2005	2007	Increase (%)
Grade 2—common	789	1,404	78
Grade 1—common	1,754	1,842	5
Select/better	3,158	3,509–4,386	9–39
Select/curl	4,386	5,263–5,614	20–28
Full curl	5,263	7,018	33
Premium curl	7,895	8,772	11
Instrument grade	11,404	17,544	54
Koa logs $<$ 0.6 m long	1,053	1,053	0
Koa logs $\geq$ 2 m long[a]	1,053	1,228–2,105	16–100

Source: personal interviews of Hawaii-based loggers and retailers by NS Dudley

[a] High-quality logs with lengths of 2 m or more are currently in short supply in the marketplace

A key assumption in the recent financial analyses of Loudat and Kanter (1997), Hensley (2002) and Goldstein et al. (2006) is that koa stands, regardless of their origin (natural or planted), will yield a particular minimum volume and quality of merchantable wood at rotation age. Casual observations indicate that few plantations contain large proportions of well-formed trees that might 1 day yield sawlogs. Instead, plantation trees generally appear to have multiple trunks originating within 3 m of ground level (Fig. 1), a growth form unlikely to yield much merchantable wood. This paper examines the appropriateness of the assumed volume yield of 135 m^3/ha at 45 years (Goldstein et al. 2006) for selected koa plantations in Hawaii.

The objectives of this study were to (1) estimate present gross merchantable sawtimber volumes in three 18- to 28-year-old koa plantations, (2) project those estimates forward to a rotation age of 45 years and (3) compare the projected volume yields with the assumed yield of 135 m^3/ha (Goldstein et al. 2006). The implications of the findings with regard to the projected financial outcomes of the alternative business strategies analyzed by Goldstein et al. (2006) are discussed.

Fig. 1 Plantation grown *Acacia koa* typically fork close to the ground resulting in short butt logs that contain little sawtimber volume. *Source*: Photo by JB Friday

Factors that might contribute to poor stem form of planted koa are reviewed, and research for determining the relative importance of and interactions between those factors and their mitigations are briefly discussed.

Study Sites and Research Method

Three small-scale koa plantations were sampled on the east flank of Mauna Kea: Umikoa Ranch, Magnetic Hill and Keanakolu. Location and establishment information for each is provided in Table 2. All are situated in upland areas with similar climate and history of degradation by cattle grazing, and all have an understory of introduced pasture grasses only, principally kikuyu grass (*Pennisetum clandestinum*), meadow ricegrass (*Ehrharta stipoides*) and sweet vernal grass (*Anthoxanthum odoratum*). Only the Umikoa Ranch plantation had been established specifically for growing koa sawlogs. The plantings at Magnetic Hill inside Hakalau Forest National Wildlife Refuge was for bird habitat. The Keanakolu plantation was originally intended as a seed orchard, and the planting stock came from several mature trees of superior size and stem form (Skolmen et al. 1991). All interior trees in each plantation were measured, except at Umikoa Ranch where four randomly located plots were used to sub-sample the plantation; the size of each rectangular plot was adjusted so that it contained at least 25 live trees. All of the plantations, excepting Umikoa, were laid out in blocks, which were used as sampling units for statistical characterization of butt log sizes, tree densities and sawtimber volumes per hectare.

For each live tree in 2008, measurements were made of stem diameter at breast height (1.4 m), height to the first live fork, crown dominance class (following the definitions of Oliver and Larson 1990, p. 148) and the nature and number of butt-log and crown defects. An individual tree was judged to have potential as a future crop-tree if it had a straight, clear, defect-free butt log that was unforked to at least 3 m above ground and a full, healthy, dominant or co-dominant crown.

Gross butt-log wood volumes of (1) crop trees only and (2) all dominant and co-dominant crop and non-crop trees that had heights to first live fork more than 2 m were estimated by two alternative methods. The first method used the International ¼-inch log rule, a Girard form class of 78 (following Mesavage and Girard 1946) and the equation (Eq. 1) developed by Wiant (1986):

$$\begin{aligned} V_W = {} & (1.52968L^2 + 9.58615L - 13.35212) + ((1.7962 - 0.27465L^2 \\ & - 2.59995L)\text{DBH}) + ((0.04482 - 0.00961L^2 + 0.45997L)\text{DBH}^2) \end{aligned} \quad (1)$$

where V_W is the log-rule gross volume of the merchantable trunk length (board foot (bf)/tree), DBH is stem diameter outside bark at breast height (inches [1 inch = 2.54 cm]), and L is the number of 16-ft-long logs (4.9 m) in the trunk below the first live fork. The last was calculated by first subtracting from height to first live fork 1 ft (0.3 m) for stump height and 0.7 ft (0.2 m) to allow for the top cut being made below the first live fork. Then the adjusted merchantable length of trunk was divided by 16 ft, which is the standard length of a full log in the USA.

Table 2 Descriptions for three plantations established in abandoned pasture on the east flank of Mauna Kea volcano, island of Hawaii

Plantation name	Lat/lon	Elevation (m)	US soil classification	Year planted	Size (ha)	Spacing (m)	Seed source	Purpose
Umikoa Ranch	19°57′N/155°20′W	1,250–1,420	Hydrous, ferrihydritic, isomesic Acrudoxic Hydrudands	1990	180	2.1 × 2.7	Bulk	Sawtimber
Magnetic Hill	19°48′N/155°20′W	1,980	Medial over hydrous, ferrihydritic, isomesic Acrudoxic Hydrdands	1987	2	2.0 and 2.5	Bulk local	Experimental
Keanakolu	19°55′N/155°20′W	1,610	Medial, amorphic, isomesic Dystric Haplustands	1980/1984	0.25	2.0 × 2.0	Plus trees	Plus-tree seed orchard

Conversion of volume from board feet (bf) to cubic meters was done by multiplying bf by 0.0057 m^3/bf (following USDA 1949).

The second method for wood volume estimation used Huber's equation (Eq. 2) to estimate gross merchantable volume of crop trees:

$$V_M = \frac{1}{10,000} \times \frac{\pi}{4} \times \left(\frac{\mathrm{DBH}^2 + D_{\mathrm{Top}}^2}{2}\right) \times H_{\mathrm{Log}} \tag{2}$$

where V_M is the merchantable volume (m^3), DBH is the stem diameter at breast height (cm), D_{Top} is the diameter at the top of the butt log (cm), and H_{Log} is the adjusted merchantable length of trunk (m). H_{Log} was estimated as described for Wiant's equation. Stem diameter at the top of the log was estimated using a linear equation (Eq. 3; $r^2 = 0.89$) developed from unpublished data (on file with Scowcroft) collected during the harvest of 51 randomly selected dominant and co-dominant koa trees from 15 to 17-year old secondary stands that were located in an area climatically similar to that of the plantation sites.[1]

$$D_{\mathrm{Top}} = -2.76 + 1.02 \times \mathrm{DBH} \tag{3}$$

Individual tree volumes for 2008 were projected forward to a common stand age of 45 years by assuming that (1) the lengths of butt logs (i.e. height to first live fork) did not change from their 2008 values, and (2) DBHs of dominant and co-dominant trees at all three study sites increased at the rate of 0.5 cm/year. This was the average DBH growth rate for 20 to 40-year-old koa trees in two permanent plots (plots 23 and 41) established by the Hawaii Division of Forestry and Wildlife (Constantinides 2003) in areas climatically similar to the three study sites. Present and projected individual tree volume estimates were scaled to volume per hectare by multiplying average volume per tree by tree density, which assumes that all crop trees survive to an age of 45 years. The percentage by which the projected volumes (V_W or V_M) fell short of or exceeded the assumed level of 135 m^3/ha (following Goldstein et al. 2006) were calculated as $(1 - V/135) \times 100$.

Research Results

Few plantation trees were classified as potential crop trees for sawtimber in 2008. One-half to two-thirds of the trees were classified as dominant or co-dominant individuals with 4–20% of them meeting the crop tree criteria (Table 3). Presence of a major fork within 3 m of the ground was the most common reason that dominant and co-dominant trees were disqualified as crop trees: approximately 80% of the trees in the Umikoa and Magnetic Hill plantations, and 48% in the Keanakolu plantation had a major fork below 3 m. Stem defects (decaying, unsound branch and fork remnants, swollen stems, unhealed wounds and curved trunk) were the next most common reasons for disqualification. Only 1% of the dominant and

[1] The Huber method of estimating wood volume is included here because the KOA model, which was developed by Grace (1995), uses the Huber method, and that model has been used in Hawaii to estimate potential koa volume yields (e.g. Ares et al. 2008).

Table 3 Average density and basal area of koa trees classified as (a) suppressed and intermediate (S&I), (b) dominant and co-dominant (D&C) crown classes and (c) potential crop trees, and the proportion of dominant and co-dominant trees that were classified as crop trees in 2008 in three plantations

Plantation name	Present age (years)	Sample size[a]	Density (sph)			Proportion of D&C (%)	Basal area (m^2/ha)			Proportion of D&C (%)
			S&I	D&C	Crop trees		S&I	D&C	Crop trees	
Umikoa	18	4	139 (32)[b]	282 (34)	25 (15)	9 (6)	6.6 (2.2)	29.1 (4.5)	1.7 (1.1)	7 (5)
Magnetic Hill	21	30	566 (62)	646 (43)	30 (10)	5 (1)	11.0 (1.2)	38.9 (2.1)	1.5 (0.6)	3 (1)
Keanakolu	24–27	6	289 (114)	511 (128)	101 (42)	20 (6)	11.0 (3.3)	67.8 (13.9)	10.0 (4.3)	15 (5)

[a] Number of planting units contained or sampled within each plantation; each unit contained at least 25 trees at time of establishment

[b] Standard errors are shown in parentheses

co-dominant trees in each plantation were disqualified because of a crown defect, such as active dieback.

In 2008, stand basal area for the Umikoa and Magnetic Hill plantations, both of which originated from bulk seed lots, averaged 35.7 and 49.9 m^2/ha, respectively (Table 3). The Keanakolu plantation, which consisted of the progeny of superior size and form koa parents, had the greatest stand basal area of 78.8 m^2/ha. Crop trees made up 3–15% of the basal area of dominant and co-dominant trees in these plantations (Table 3).

In 2008, butt logs were generally shorter than the US standard length of 4.9 m, the exception being the trees in the Keanakolu plantation (Table 4). Crop-tree log length averaged 3.7 m in the Magnetic Hill plantation, 4.2 m in the Umikoa plantation, and 5.1 m in the Keanakolu plantation. Average DBH ranged from 24 cm for the Magnetic Hill plantation to 39 cm for the Keanakolu plantation. Corresponding merchantable wood volumes ranged from 0.15 to 0.58 m^3/butt log. Average projected volumes were 2.4, 2.5, and 1.5 times as great as the volumes in 2008.

The combination of a low density of crop trees and short length of butt logs resulted in estimates of gross merchantable wood volume from each plantation that fell below the assumed value of 135 m^3/ha used by Goldstein et al. (2006) (Table 5a). In 2008, potential crop trees in the Umikoa and Magnetic Hill plantations contained 4.2–6.5 m^3/ha, respectively. In comparison, crop tree volume at Keanakolu was approximately 10 times as high (55 m^3/ha). Projected crop tree volumes at 45 years of age ranged from 10 to 11 m^3/ha at Magnetic Hill to 90–92 m^3/ha at Keanakolu, depending on the method used to estimate volume. The shortfalls in projected volumes at 45 years of age relative to the assumed value of 135 m^3/ha (Goldstein et al. 2006) averaged close to 90% at Umikoa and Magnetic Hill, and approximately 33% at Keanakolu. These shortfalls were the same regardless of the method used to estimate log volume (Table 5a).

The impact of low crop tree density and low fork heights of plantation koa was still apparent when the criteria for crop trees were relaxed to allow inclusion of any dominant or co-dominant tree with height to first live fork above 2 m, regardless of butt-log or crown defects. Projected merchantable volumes at 45 years for the Umikoa and Magnetic Hill plantations still fell short of 135 m^3/ha assumed by Goldstein et al. (2006) by 50–67%, depending on the volumetric formula used

Table 4 Average present (2008) and projected future (45-years-old) butt log length, DBH and volume for potential koa crop trees (straight trunks with clear boles >3 m in length) in three plantations

Plantation name	Present age (years)	No. of 4.9-m logs/tree	DBH (cm)		Volume[a] (m^3/tree)	
			Present	Future	Present	Future
Umikoa	18	0.85 (0.09)[b]	28.4 (1.5)	42.2 (1.5)	0.25 (0.05)	0.59 (0.08)
Magnetic Hill	21	0.75 (0.12)	24.1 (2.5)	36.3 (2.5)	0.15 (0.03)	0.37 (0.04)
Keanakolu	24–27	1.04 (0.07)	38.9 (2.0)	47.5 (2.0)	0.58 (0.06)	0.89 (0.07)

[a] Volume estimated using the International ¼-inch rule and the equation of Wiant (1986) for stem form class 78

[b] Standard errors are shown in parentheses

Table 5 Estimated present (2008) and future (45-years-old) gross merchantable sawtimber volumes for (1) potential koa crop trees only and (2) all crop and dominant and co-dominant non-crop trees in three plantations

Plantation name	Present age (years)	Tree density (sph)	Volume (Intl ¼-inch rule)			Volume (Huber's formula)		
			Present (m^3/ha)	Future	Shortfall[a] (%)	Present (m^3/ha)	Future	Shortfall[a] (%)
Crop trees only								
Umikoa	18	25 (15)[b]	6.5 (4.3)	15.5 (9.9)	88 (7)	6.5 (4.3)	14.5 (9.4)	89 (7)
Magnetic Hill	21	30 (10)	4.5 (1.8)	11.1 (3.9)	92 (3)	4.2 (1.5)	9.7 (3.3)	93 (2)
Keanakolu	24–27	101 (42)	55.4 (20.2)	91.7 (35.1)	32 (26)	56.1 (20.6)	90.3 (34.6)	33 (26)
Crop and non-crop trees								
Umikoa	18	136 (25)	35.6 (6.1)	79.1 (11.0)	41 (8)	30.0 (4.7)	64.4 (8.5)	52 (6)
Magnetic Hill	21	289 (37)	32.8 (5.0)	90.3 (12.8)	33 (9)	31.2 (4.8)	77.0 (11.4)	43 (8)
Keanakolu	24–27	303 (59)	152.7 (22.2)	258.2 (43.6)	*92 (32)*	156.9 (24.0)	260.1 (47.5)	*93 (35)*

Only non-crop trees that forked above 2 m are included

[a] Percentage by which the future volume falls short of or exceeds (*italicized numbers*) an assumed target level of 135 m^3/ha

[b] Standard errors are shown in parentheses

(Table 5b). In contrast, relaxing the criteria for crop trees resulted in project wood volumes for the Keanakolu plantation that were more than 90% greater than the 135 m^3/ha assumed by Goldstein et al. (2006).

Discussion

The financial analyses of koa forestry in Hawaii done by Loudat and Kanter (1997), Hensley (2002) and Goldstein et al. (2006) indicate that landholders can expect modest and perhaps even large returns on investment. The most recent analysis (Goldstein et al. 2006) assumed that koa stands regenerated naturally from buried seeds following soil scarification. Might landholders expect koa plantations to yield similar returns on investment? Perhaps, but only if the costs of establishing and tending plantations are comparable to the costs of establishing and tending naturally regenerated stands, and only if the merchantable volume yields are comparable. Results of this study suggest that merchantable volume yields from plantations will be substantially less than from naturally regenerated stands. So even if establishment and tending costs are similar, financial returns on investment will be smaller for plantations, as the following section illustrates.

Implications for the Most Recent Financial Analyses

Poor stem form of plantation-grown koa resulted in low densities of potential crop trees, short butt logs, even for crop trees, and consequent shortfalls in projected merchantable wood volumes of 33–90% relative to the assumed yields of Goldstein et al. (2006). Even when the crop tree criteria are relaxed, shortfalls of 33–50% are still projected for two of the plantations. Lower merchantable wood volume should reduce the net present values (NPV) reported by Goldstein et al. (2006). They estimated a mean NPV of $1,119/ha for timber production alone (Table 6), without any type of financial incentive, which is substantially more than the land's opportunity cost in cattle ranching of $479/ha. The NPV increases to $1,846/ha when timber production is combined with the incentive provided by the State of Hawaii Forest Stewardship Program (*FSP*), which is a government cost-sharing program designed to offset a portion of land management costs associated with enhancing the value of forest resources. The management strategy with the greatest NPV ($4,104/ha) combines timber production with the financial incentives of the US Department of Agriculture's, Conservation Reserve Enhancement Program (*CREP*), which provides government rental payments and cost-share assistance to cover initial forest establishment and continuing major maintenance costs incurred during conversion of agricultural land to forest.

The estimates of koa wood volume for the three plantations fall well short of those assumed by Goldstein et al. (2006). The Magnetic Hill and Umikoa plantations were established from bulk seed lots and projected yields fall 90% short of the target level used by Goldstein et al. Such a shortfall would reduce the NPV for the timber-alone strategy (*T*) from $1,119/ha to about $112/ha (Table 6). This

Table 6 Estimated net present value (NPV) of four alternative business strategies and the potential effect on NPV of lower merchantable wood volumes than assumed in the original financial analyses (Goldstein et al. 2006), by plantation

Business strategy	Estimated NPV[a] (US $)	Value added by incentive[b] (US $)	Hakalau and Umikoa plantations		Keanakolu plantation	
			Volume shortfall[c] (%)	Reduced NPV[d] (US $)	Volume shortfall[c] (%)	Reduced NPV[d] (US $)
Cattle ranching	479	–	–	–	–	–
Timber (*T*)	1,119	–	90	112	33	750
T + *FSP* incentive	1,846	727	90	839	33	1,477
T + *CREP* incentive	4,104	2,985	90	3,097	33	3,735

FSP Forest Stewardship Program, *CREP* USDA Conservation Reserve Enhancement Program (see discussion for additional information about the two government incentives)

[a] Estimated NPV derived from Goldstein et al. (2006)

[b] Value added by incentive = estimated $\mathrm{NPV}_{T+\mathrm{Incentive}}$ − estimated NPV_T

[c] The percentage by which the projected sawtimber volumes at 45 years old (*V*) fell short of the assumed level of 135 m^3/ha as specified by Goldstein et al. (2006); the shortfall was calculated as $(1 - V/135) \times 100$

[d] Value added by incentive plus reduced NVP_T

lower NPV is 77% less than the land's opportunity cost in cattle ranching ($479/ha). For the *T* + *FSP* strategy, the NPV would be reduced to $839/ha, and for the *T* + *CREP* strategy the NPV would be about $3,097. In both cases, the revised NPV exceeds that of cattle ranching alone, and any additional costs associated with plantation establishment are unlikely to change this ranking. Furthermore, the value added by government incentives alone ($727 for *FSP* and $2,985 for *CREP*; Table 6) leads to those strategies having greater NPVs than cattle ranching alone, even if timber harvest never occurs.

The projected shortfall in wood volume was substantially less for the Keanakolu plantation (33%) where the progeny used in plantation establishment came from seed trees of superior size and stem form. The reductions in estimated NPVs (Goldstein et al. 2006) were also correspondingly less. The reduced NPV for the timber-alone (*T*) strategy was $750/ha (Table 6), which is $271/ha greater than cattle ranching alone. Similarly, the reduced NPV was $1,477 for the *T* + *FSP* strategy and $3,735 for the *T* + *CREP* strategy (Table 6). The data from the Keanakolu plantation clearly indicate that greater merchantable wood volume and hence greater returns on investment can be realized by using genetically superior planting stock.

Factors Influencing Stem Form

The primary cause of reduced stem wood volume in koa plantations is poor tree form. Fifty to eighty percent of the plantation trees in this study were excluded as

potential crop trees because of poor stem form. Several factors are believed to contribute to this problem, as reviewed below.

Insect Herbivory

Aside from large animal herbivores, which have obvious adverse effects on stem form (Tunison et al. 1995), recent introductions of insect herbivores present problems that did not exist when old-growth forests were developing. Perhaps the most serious insect herbivore threat to straight, unforked clear trunks is the Acacia psyllid, *Acizzia uncatoides*, which arrived in Hawaii in 1966 (Leeper and Beardsley 1973). It breeds and feeds on new terminal shoot growth (Leeper et al. 1981), and predators including ladybird beetles (coccinellids) are unable to check periodic outbreaks (Leeper and Beardsley 1976). Defoliated terminal shoots die back, and each is replaced by multiple new shoots that develop later in the growing season. Repeated attacks during the early years of stand development produce trees with multiple forks close to the ground and full but bushy crowns. Even small plantations of hundreds or a few thousands of individual koa trees may allow psyllid populations to build up to the point where all trees in a stand will be affected.

Genetics

Progeny trials have indicated that although there is a genetic component to koa stem form, few planted trees exhibit desirable stem form for sawtimber. Brewbaker (1997) found that 90% of his 500 seed accessions produced only multi-stem progeny. Daehler et al. (1999) reported that 55–71% of the trees grown in common gardens developed a major fork in the trunk within 0.3 m of the ground, despite having maternal parents with good stem form. Although Brewbaker (1997) stated that a high degree of self-fertilization occurs within local koa provenances and families, genetic diversity is still greater within populations than between populations. As a result, large variations in growth rates and tree form among half-sib families are normal (Sun 1996). Thus, it is not surprising that few plantation koa trees have desirable stem form, especially if they originate from bulk seed lots collected without regard to stem form or timber quality.

Data from the Keanakolu plantation illustrate that while there is a genetic component to good stem form and volume yield, other factors can hinder its expression. Projected merchantable volume of this plantation was 6–8 times as high as that of the other plantations examined in this study. Yet the yield was only two-thirds as large as the assumed value of 135 m^3/ha used by Goldstein et al. (2006). The problem is, in part, the failure of the progeny to develop lengths of clear bole as great as their parents. Four parent trees located in mixed species native forest approximately 1 km from of the plantation had clear stems ranging in length from 11.6 to 21.0 m (Fig. 2). Their progeny at 5–6 years of age generally forked within 3 m of the ground. Twenty-one years later, average height to the first live fork had increased, but relative to the parents, most survivors still had short lengths of clear stem even though they had reached two-thirds the total height of the parents. The original fork was visible on 90% of the trees, and it was still alive on 36% of them.

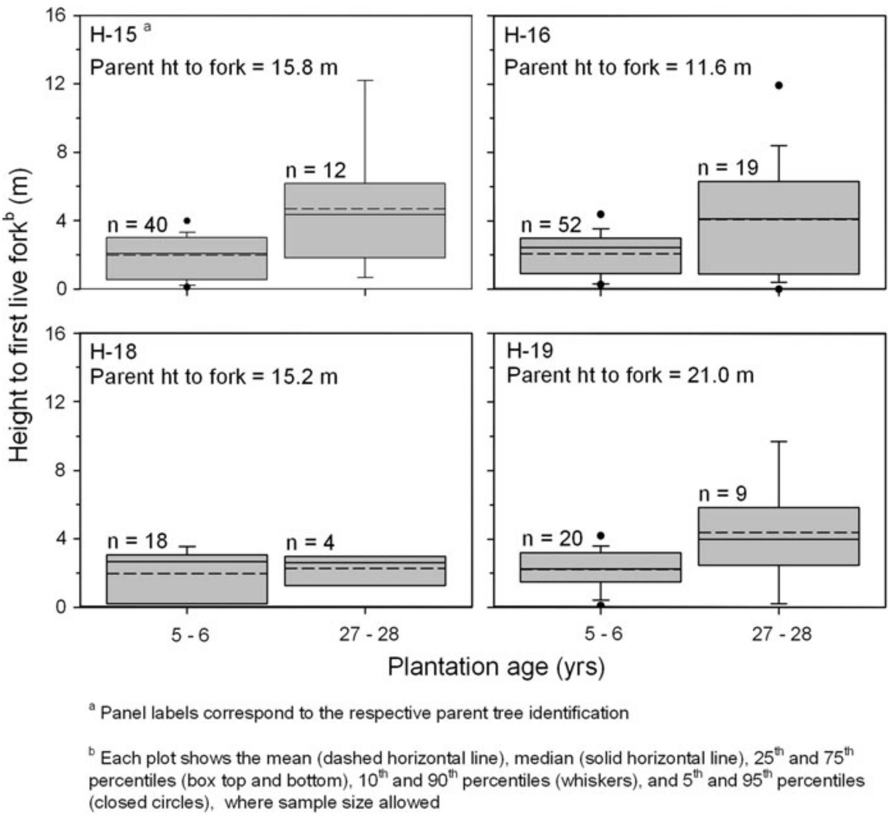

Fig. 2 Height to first live fork in the Keanakolu plantation for 5–6 and 27–28 year-old dominant and co-dominant progeny of four superior-size old-growth *Acacia koa* parent trees

The scientist who established the Keanakolu plantation attributed low forks to repeated and heavy attacks on new shoot growth by the Acacia psyllid (R. G. Skolmen, personal communication, 2007). Thus, relying on genetic selection or manipulation of stand density to improve stem form of planted koa may be futile if no solution to such insect herbivory can be found (Shi and Brewbaker 2004).

Stand Density

Weak apical dominance is probably a contributing factor in poor stem form of koa, especially in widely spaced plantations. Evans (1992, p. 182, 225) noted that in broadleaved plantations wider spacing often results in poorer tree form, and light-demanding species including koa that develop large crowns in full light require dense planting to encourage carbon allocation to height growth (rather than to lateral crown spread), straight stems and shedding of lower branches and weaker forks.

Initial spacing in koa plantations typically ranges from 2 × 2 m to 3 × 4 m. As a result, initial tree density in plantations (800–2,500 stems/ha) is lower than that found in naturally regenerated stands, which can exceed 10,000 sph (Skolmen and

Fujii 1981). These differences in initial stand density lead to several important differences in stand dynamics. First, canopy closure typically occurs later in plantations. Second, at canopy closure, tree size and growing space occupied per tree tend to be greater for plantations. Although growth slows after canopy closure in all types of stands, the decline is generally slower in less dense stands (Oliver and Larson 1990). Finally, natural density-dependent thinning usually begins later and stand density declines more slowly in plantations than in natural stands.

These differences in stand dynamics likely affect stem form. For example, densities of four naturally regenerated koa stands on Hawaii Island converged to 700–900 trees/ha after 24 years even though initial densities varied from 5,000 to 20,000 trees/ha (P. G. Scowcroft, unpublished manuscript, 2002). Based on the growing space principles described above, the densities of plantations at 24 years should be similar to natural stands on similar sites. This implies that at a spacing of 3×4 m (833 sph), most plantation trees would have had enough growing space to remain alive, although some would have declined in vigour and moved into suppressed and intermediate crown classes. However, some forks that would be suppressed in initially dense natural stands would continue growing in plantations, and lower branches would be retained longer and reach larger diameters (Oliver and Larson 1990).

Research Needed to Improve Stem Form of Planted Koa

The relative importance of each factor discussed above to poor stem form in koa plantations is unknown. There might be other factors at work too. Improving stem form will depend on gaining a greater understanding of the roles played by those factors and their interactions.

Assessing the Impact of Insect Herbivory

Studies are needed to determine the role of the Acacia psyllid in promoting low stem forking. If research confirms that the psyllid is a major contributor to poor stem form, as suspected, then the next step would be to determine if anything can be done to overcome this problem. Mitigation might involve biological control agents, insecticides and selection of resistant koa genotypes.

Genetic Tree Improvement Research

There has been interest in genetic improvement of koa for at least 40 years (Brewbaker et al. 1991), but efforts to achieve improvement have not progressed to the point of being able to provide landholders with superior planting stock. Efforts are needed to evaluate existing and new koa families and provenances with consideration being given to stem form and wood quality as well as to growth rate and disease resistance. The adverse effect of insect herbivory on stem form might mask genetic predisposition to production of single unforked stems. Research is needed to tease apart this interaction.

Glover et al. (1991) stressed the importance of having clonal material to study heritability of tree form as well as other traits of interest. Although vegetative propagation techniques have shown some promise (Skolmen 1977, 1978; Sun 1996; Shi 2003) more work is needed before the techniques becoming standard practice. In particular, vegetative propagation of mature phyllodinous koa has not been successful, except for air-layering of root suckers before they begin producing phyllodes (Skolmen 1977; Shi 2003). The applicability of micropropagation and vegetative propagation techniques used successfully with other tropical acacias (e.g. Darus 1992; Wong and Haines 1992) is unknown.

Silvicultural Research Options for Improving Stem Form

Like other hardwood tree species with weak apical dominance, initial stand density probably affects stem form of koa. Research is needed to determine if greater initial stand density in plantations (i.e. greater crowding from the sides) favours development of straight, single stem boles that are defect-free to at least 3 m above ground level. Research on the use of nurse crops to foster development of single-stem koa similar to what has been done for *Acacia melanoxylon* (Unwin et al. 2001) and *Juglans regia* (Clark et al. 2008) might also be appropriate. Although most existing koa plantations seem to have little value for sawtimber, they might have value as nurse crops for the next generation of koa. Although underplanting would not work for shade-intolerant koa, it might be possible to created gaps in the canopy of existing plantations and then plant seedlings into them or scarify the soil in them to stimulate germination of buried seeds. The effect of gap size might be a focus of the research.

Research to determine the effectiveness of corrective (formative) pruning to encourage the development of a single straight stem before canopy closure has not been done for koa. Definitive studies on the efficacy and cost-benefit of pruning koa for stem form are needed.

Concluding Remarks

In Hawaii, projected merchantable volume yields from koa plantations appear to be too low to support investment without some form of monetary incentive. With effective and sustained incentive programs, such as *FSP* and *CREP*, poor stem form of plantation koa need not deter private investment. Furthermore, loggers in Hawaii have become adept at profitably extracting small dimension material, even excavating around koa trees to get as much of the base of the trees as possible. Although not suited for sawtimber, which was the basis for the present study, such small dimension stock can be valuable depending on its wood grade. The need for research to establish the causes of poor stem form in koa plantations and to develop cost-effective mitigations against those factors will increase as supplies of old growth material disappear. Likewise, it will become increasingly important that the public and private sectors collaborate to support efforts that lead to a sustainable supply of koa wood to meet market demand.

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